Beam Spread Analysis

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LONG-TERM GOALS

My long-term goal is to support the work of ocean optics experimentalists by developing analytical and numerical methods for solving forward and inverse radiative transfer problems. This research contributes to the technology for underwater imaging and for characterizing the optical properties of different waters.

OBJECTIVES

The objective of this project is to investigate the spreading of monochromatic light away from a localized beam source sufficiently deep that surface illumination effects are negligible in comparison to the strength of the source. Because probabilistic (i.e., Monte Carlo) methods exist for solving this problem, my objective is to develop and numerically test methods using deterministic (i.e., non-Monte Carlo) methods for numerically predicting experimental results for the light field away from a collimated laser beam source in ocean waters. The specific objective is to predict the detector radiance and planar irradiance as a function of position away from the axis of the beam source under conditions in which the detector is or is not oriented along the axis between the detector and point from which the beam is emitted.

The collimated beam illumination problem is one of the most fundamental of all problems in ocean optics, with applications to the determination of inherent optical properties and the imaging of underwater objects. The light field away from a localized source emitting a collimated beam of radiation gives (e.g., Ref. 1) the beam spread function (BSF). A BSF experiment is done by scanning with a plane irradiance detector away from the path of uncollided radiation emitted from a beam source. The BSF problem traditionally has been analyzed by means of Monte Carlo methods because the geometry is very complicated and not compatible with standard ocean optics computer programs such as Hydrolight (Ref. 2). Some earlier oceanographic analyses (e.g., in Refs. 3-5) have assumed a small-angle scattering model for the phase function, but in this project that assumption is avoided so that a variety of Case 1 and Case 2 waters can be investigated.

APPROACH

My approach is to develop a discrete ordinates computer program capable of predicting the radiance from a highly collimated beam source. The discrete ordinates method was selected as an alternative to the Monte Carlo method of solving problems because it is not subject to errors associated with sampling statistics. But we have found there are problems with the method for ocean optics applications because of the severely anisotropic scattering of ocean waters. The strongly anisotropic

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14. ABSTRACT
My long-term goal is to support the work of ocean optics experimentalists by developing analytical and numerical methods for solving forward and inverse radiative transfer problems. This research contributes to the technology for underwater imaging and for characterizing the optical properties of different waters.

15. SUBJECT TERMS

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scattering and the highly singular nature of the "pencil" beam illumination from the localized point source has caused other analytical methods, investigated early during the project, to be abandoned.

The radiative transfer equation is solved in curvilinear spherical coordinates. Because of the symmetry of rotation with respect to the beam axis, two variables (the distance between the beam emission point and the detector, as well as the polar angle) locate the receiver with respect to the source. Two other variables (the polar and azimuthal angles) specify the detector orientation with respect to the axis between the source emission point and detector. Once the radiance reaching the detector has been determined one must integrate the outward radiance over the surface of the detector to determine the outward plane irradiance, for example.

With the discrete ordinates prescription we use an angular quadrature formula to discretize the collision term of the radiative transfer equation. The result is a set of ordinary differential equations coupled through the collision term that is well suited for an iterative solution on the scattering source. The spatial discretization is obtained by writing exact cell balance equations in terms of cell and surface mean values of the radiance and by introducing the familiar diamond approximations across the cell to achieve finite differencing on the spatial variables as well as across the angular cell for the angular variables For our calculations we have used strongly biased polar quadrature formulas with an accumulation of quadrature points near the forward scattering direction.

The discrete ordinates computer program is being developed with Richard Sanchez of the Commissariat a l'Energie Atomique (Saclay, France) who has over 20 years experience programming the transport equation in a wide variety of applications for photons and neutrons.

WORK COMPLETED

As a first step in this investigation, the effective source arising from the first collided radiation beneath the sea surface was derived to improve the capability of treating the severely anisotropic scattering present in ocean waters (Ref. 6). Two other manuscripts on the results of the project, one detailing the computational procedure and the other illustrating the results for sample ocean water models, are in preparation.

RESULTS

In spherical coordinates the coordinate mapping for the first-collided component of the radiance is singular at the origin, but it was shown that with care the delta functions in direction that arise from such a source can be manipulated to give the correct results (Ref. 6). With the program developed, six orders of magnitude or more change in the detector response due to scattered photons can be predicted for different detector locations while simultaneously computing very small changes for different detector orientations. This capability is useful when assessing the sensitivity of the detector response to the independent variables of the problem.

IMPACT/APPLICATION

Prediction of the radiation field away from a localized source has significant applications for the imaging of underwater objects and for the determination of inherent optical properties. The ability to perform such predictions without the use of Monte Carlo methods will enable accurate computational results at intermediate and large optical distances from the source without statistical uncertainties.

RELATED PROJECTS

Additional developments in support of the long-range objective of developing solution methods for forward and inverse problems of radiative transfer also have been underway this year with a graduate student. The use of a linked set of equations for sequentially determining the albedo of single scattering, the mean cosine of a single scattering, the backscattering fraction, and the beam attenuation coefficient from radiance measurements is being numerically investigated.

With Curtis Mobley of Sequoia Scientific, Inc., I prepared definitions for ocean optics that were included in Ref. 7. I also conducted a graduate-level tutorial course for James Coleman, USN, through the University of Washington School of Oceanography and I provided input to Howard Gordon of the University of Miami for a review paper on inverse problems in ocean optics that he has prepared.

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PUBLICATIONS

R. Sanchez, On the singular structure of the uncollided and first-collided components of the Green's function, Ann. Nucl. Energy **27**, 1167-1186 (2000).